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Our research is focused on defining robust adaptive control architectures that can be completely characterized with their performance bounds and robustness/stability margins. Research in this direction over the past several years has led to a powerful set of tools, known as L1 adaptive control theory. This new paradigm for design of adaptive control systems embeds the robustness specification explicitly into the control problem formulation (control objective) and allows for decoupling adaptation from robustness, limiting the speed of adaptation only by available hardware (CPU). The performance bounds can be predicted a priori based on the conservative bounds of uncertainty, and the time-delay margin of it can be tuned systematically. The results of this research have been leveraged into different programs across the country, including WP AFRL's "Certification of Advanced Flight Critical Systems: Challenge Problem Integration" and NASA's "Integrated Resilient Aircraft Control".

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ROBUST ADAPTIVE CONTROL OF MULTIVARIABLE NONLINEAR SYSTEMS

FA9550-09-1-0265

FINAL REPORT

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Abstract: Our research is focused on defining robust adaptive control architectures that can be completely characterized with their performance bounds and robustness/stability margins. Research in this direction over the past several years has led to a powerful set of tools, known as L_1 adaptive control theory. This new paradigm for design of adaptive control systems embeds the robustness specification explicitly into the control problem formulation (control objective) and allows for decoupling adaptation from robustness, limiting the speed of adaptation only by available hardware (CPU). The performance bounds can be predicted a priori based on the conservative bounds of uncertainty, and the time-delay margin of it can be tuned systematically. The results of this research have been leveraged into different programs across the country, including WP AFRL's "Certification of Advanced Flight Critical Systems: Challenge Problem Integration" and NASA's "Integrated Resilient Aircraft Control". We also revealed some similarities with the disturbance observer (DOB) controllers and identified the main features in the difference between them. The key feature of this difference is that the estimation loop of the L_1 adaptive architectures reconstructs the inverse map of the DOB architecture by fast estimation and with that avoids the number of challenges of DOB related to the plant inversion. Insights from this comparison were used towards modification of DOB with improved transient performance.

Technical Transitions: We had the opportunity to transition our theoretical work to various applications, including both military and commercial sections. On the military side, our collaboration with NPS led to a flight test of two UAVs (with complementary sensing capabilities) in a time-critical coordinated road search maneuver in TNT exercises in Camp Roberts, CA[1]. On the commercial side, the implementation of L_1 adaptive controller on NASA's subscale generic transport model (GTM) aircraft demonstrated *repeatable and predictable* (i.e. verifiable) results in multiple high-angle of-attack acquisition tasks by a pilot[2]. The flights included variations in speed up to post-stall flight regimes, and the performance was achieved with a *single* design of the control parameters in L_1 adaptive controller, without resorting to gain-scheduling, control reconfiguration or persistency of excitation. These flight tests clearly validated the *uniform* performance bounds of L_1 adaptive controller from one flight test to another.

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[1] Leveraged by ONR and USSOCOM
[2] Leveraged by NASA's IRAC Program

Main accomplishments: We developed the L_1 adaptive control theory, summarized in [1], and transitioned it to various applications, by leveraging additional sources of funding for that. They key idea of this theory is to decouple the identification loop from the feedback control by means of an architecture so that fast estimation rates can be used for improved performance without sacrificing robustness. The theory has been developed for state feedback and output feedback controllers, for linear and nonlinear systems, in the presence of unmodeled dynamics and time-varying nonlinearities, without restricting the rate of their variation. The architectures of this theory enable to reduce the performance limitations to the hardware limitations. The main challenge is to design the low-pass filter for optimizing the tradeoff between performance and robustness.We explored various stochastic optimization methods for design of *optimal* filters for the L_1 adaptive controllers [2]. These results aim at developing a methodology, which can benefit from the stochastic optimization methods, like randomized algorithms, for the purpose of quickly identifying a possible local domain of the search parameters (entries of filter realization), within which deterministic gradient optimization methods with local performance guarantees can be employed effectively. We also explored the robustness margin of L_1 adaptive controllers in gap metric [3, 4]. By appropriately extending the classical notion of stability from [5] to accommodate biased-gain stability, our results show that the robustness margin of L_1 adaptive controllers is guaranteed to be bounded away from zero, and can be suitably tuned via the design of the underlying filter of the L_1 adaptive controller. Moreover, the bias that quantifies the *performance of the stability* can be arbitrarily reduced by increasing the adaptation rate.

In parallel, we also initiated a new direction of research in our lab towards identifying Bode-like performance limitations for continuous-time stochastic switching systems. Our preliminary results in [6] explored a non-trivial extension of Bode-like formula from [7] to continuous-time systems. The essence of the non-trivial extension is in the fact that Kolmogorov's entropy rate inequality, which is used for derivation of the information conservation laws in discrete-time setting in [7], cannot be effectively employed in continuous-time setting due to the undesirable properties of the underlying limiting relationship. Instead one needs to resort to mutual information rate for derivation of similar conservation laws in continuous-time setting. The latter are elaborated towards obtaining a Bode-like integral for continuous-time stochastic processes.

We have also extended the theory to networked control systems to set the stage for the renewal proposal, [8-10].

Among the many applications and transitions considered over the last several years, the following are of special relevance to Air Force:

- **Military section:** Augmentation of off-the-shelf autopilots to ensure accurate path following for two UAVs executing time-critical missions within spatial constraints in the presence of *time-varying* communication network topology with complementary sensing capabilities [11]. Figure 1 illustrates those results.

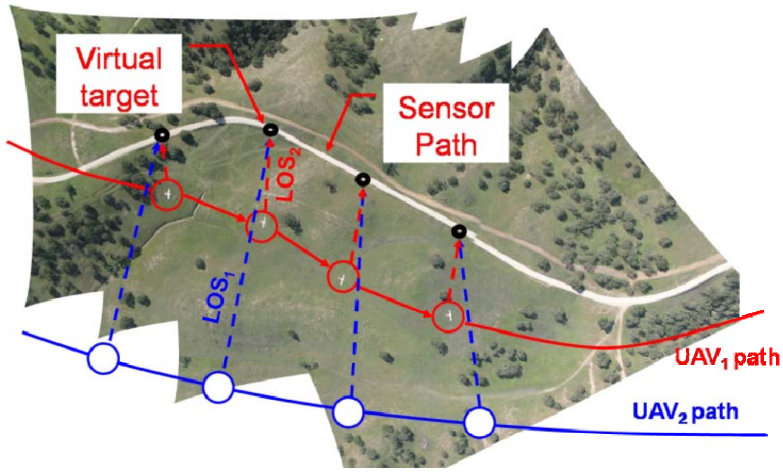

Figure 1. Time-critical coordinated path following in a coordinated road search maneuver. In this application, after a user designates a road where a potential foe is on the move, two *heterogeneous* UAVs with complementary sensors (high resolution camera and pan-tilt video camera) are dispatched to search the road and to track the target once it has been identified by the user. Accurate coordination with the help of controller is especially important to maximize the intersection of the field of view of each sensor and guarantee successful continuous coordinated coverage.

- **Commercial section:** Flight tests of a subscale commercial jet (NASA's AirSTAR flight test vehicle) in pre and post-stall flight regimes with a single design of L_1 controller without any gain-scheduling [12]. Figure 2 highlights those results.

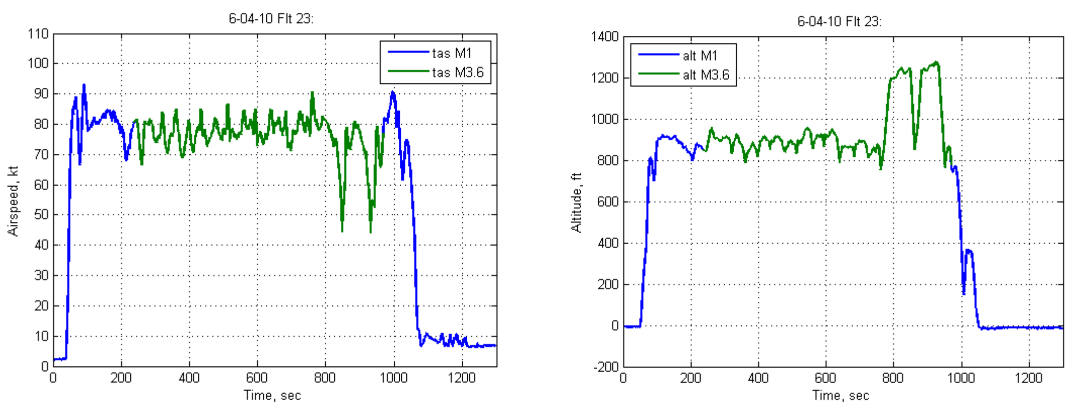

Figure 2. Flight test results of NASA's AirSTAR test vehicle: 18 degrees angle-of-attack acquisition tasks executed by the pilot. L_1 adaptive controller produces almost identical results (i.e. *predictable*, *repeatable*, and *verifiable* per the theory) in two consecutive maneuvers, with the airspeed dropping almost up to 40 knots (post-stall regime). In stick-to-surface control, the vehicle experiences pitch break at 15 degrees angle-of-attack and an aggressive departure in roll.

Acknowledgment/Disclaimer

This work was sponsored (in part) by the Air Force Office of Scientific Research, USAF, under grant FA9550-09-1-0265. The views and conclusions contained herein are those of the author and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the AFOSR or the U.S. Government.

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3. D. Li, N. Hovakimyan, T. Georgiou, Robustness of L_1 Adaptive Controllers in Gap Metric, *In Proceedings of* American Control Conference, Baltimore, MD, 2010.
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12. I. Gregory, E. Xargay, C. Cao, N. Hovakimyan, Flight Test of L_1 Adaptive Controller on NASA AirSTAR Flight Test Vehicle, *In Proceedings of* AIAA Guidance, Navigation and Control Conference, Toronto, Canada, 2010.

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1. Dapeng Li, Ph.D. student
2. Kwang-Ki Kim, Ph.D. student
3. Xiaofeng Wang, postdoctoral fellow
4. Naira Hovakimyan, Professor and Schaller faculty scholar, Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, IL

Additional publications complementing the above mentioned list:

In Journals:

1. E. Xargay, V. Dobrokhodov, N. Hovakimyan, I. Kaminer, I. Kitsios, C. Cao, I. Gregory, L. Valavani, Experimental Validation of L_1 Adaptive Control: Rohrs' Counterexample in Flight, Submitted to AIAA Journal of Guidance, control and Dynamics, 2011.
2. L. Ma, C. Cao, N. Hovakimyan, V. Dobrokhodov, I. Kaminer, Adaptive Vision-Based Guidance Law with Guaranteed Performance Bounds for Tracking a Ground Target with Time-Varying Velocity, AIAA Journal of Guidance, Control and Dynamics, vol. 33, No. 3, pp. 834-852, 2010.
3. L. Ma, C. Cao, N. Hovakimyan, C. Woolsey, W. Dixon, Fast Estimation for Range Identification in the Presence of Unknown Motion Parameters, IMA Journal of Applied Mathematics, pp. 1-25, 2010.
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5. C. Cao, N. Hovakimyan, Stability Margins of L_1 Adaptive Control Architecture, IEEE Transactions on Automatic Control, vol. 55, No. 2, pp. 480-487, 2010.
6. J. Wang, N. Hovakimyan, C. Cao, Verifiable Adaptive Flight Control: UCAV and Aerial Refueling, AIAA Journal of Guidance, Control and Dynamics, vol. 33, No. 1, pp. 75-87, 2010.
7. C. Cao, N. Hovakimyan, J. Evers, Active Control of Visual Sensor for Navigation and Guidance, Journal of Computational Management Science, Springer Operation Research and Decision Theory, No. 7, pp. 85-110, 2010.

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1. H. Sun, N. Hovakimyan, T. Basar, L_1 Adaptive Controller for Systems with Input Quantization, *In Proceedings of* American Control Conference, Baltimore, MD, 2010.
2. E. Kharisov, N. Hovakimyan, J. Wang, C. Cao, L_1 Adaptive Controller for Time-Varying Reference Systems in the Presence of Unmodeled Dynamics, *In Proceedings of* American Control Conference, Baltimore, MD, 2010.
3. E. Xargay, N. Hovakimyan, C. Cao, Piecewise Constant Adaptive Laws for L_1 Adaptive Controller in the Presence of Uncertain Nonlinear Cross-Coupling, *In Proceedings of* American Control Conference, Baltimore, MD, 2010.
4. A. Young, L. Ma, N. Hovakimyan, Time-Critical Coordination of Multiple Vehicles with Uni-Directional Communication Constraints, *In Proceedings of* American Control Conference, Baltimore, MD, 2010.
5. L. Ma, N. Hovakimyan, Cyclic Pursuit with Vision-Assisted Estimation, *In Proceedings of* American Control Conference, Baltimore, MD, 2010.
6. S.-J. Yoo, N. Hovakimyan, C. Cao, Decentralized L_1 Adaptive Control for Large-Scale Systems With Unknown Time-Varying Interaction Parameters, *In Proceedings of* American Control Conference, Baltimore, MD, 2010.
7. X. Zou, C. Cao, N. Hovakimyan, L_1 Adaptive Controller for Systems with Hysteresis Uncertainties, *In Proceedings of* American Control Conference, Baltimore, MD, 2010.
8. J. Luo, C. Cao, N. Hovakimyan, L_1 Adaptive Controller for a Class of Systems with Unknown Nonlinearities, *In Proceedings of* American Control Conference, Baltimore, MD, 2010.

9. R. Choe, E. Xargay, N. Hovakimyan, I. M. Gregory, L_1 Adaptive Control under Anomaly: Handling Qualities and Adverse Pilot Interaction, *In Proceedings of* AIAA Guidance, Navigation and Control Conference, Toronto, Canada, 2010.
10. E. Xargay, V. Dobrokhodov, I. Kaminer, N. Hovakimyan, C. Cao, I. M. Gregory, R. B. Statnikov, L_1 Adaptive Flight Control System: Systematic Design and V&V of Control Metrics, *In Proceedings of* AIAA Guidance, Navigation and Control Conference, Toronto, Canada, 2010.
11. I. A. Piacenza, E. Xargay, F. Quagliotti, G. Avanzini, N. Hovakimyan, L_1 Adaptive Control for Flexible Fixed-Wing Aircraft: Preliminary Results, *In Proceedings of* AIAA Guidance, Navigation and Control Conference, Toronto, Canada, 2010.
12. B. J. Griffin, J. Burken, E. Xargay, N. Hovakimyan, L_1 Adaptive Control Augmentation System with Application to the X-29 Lateral/Directional Dynamics: A MIMO Approach, *In Proceedings of* AIAA Guidance, Navigation and Control Conference, Toronto, Canada, 2010.

Honors

- Plenary Speaker at III International Symposium on Systems and Control in Aeronautics and Astronautics, Harbin, China, June 2010
- Keynote Speaker at ICNPAA World Congress: 8th International Conference on Mathematical Problems in Engineering, Aerospace and Sciences, São José dos Campos (SP), Brazil, July 2010
- Invited presenter at Lund Center for Control of Complex Engineering Systems, Workshop on Adaptation and Learning in Autonomous Systems, Lund, Sweden, April 2010
- Teaching a short course on L_1 adaptive control theory at Harbin Institute of Technology, Harbin, China (January 2010) and Lund University, Sweden (April 2010)

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Transitions

- The theory has been implemented on NASA's AirSTAR GTM dynamically scaled jet powered piloted aircraft and flight tested for post-stall flight regimes. POC: I. Gregory, NASA LaRC, Hampton, VA 23681, Ph: 757-864-4075, E-mail: i.m.gregory@larc.nasa.gov.
- The theory has been used to augment an existing autopilot (Piccolo) for accurate path following in the problem of time-critical cooperation of UAVs with spatial constraints in the presence of time-varying communication network topology. POC: Isaac Kaminer, MAE, NPS, Monterey, CA 93943, Phone: 831-656-3459 (further transition to USSOCOM in TNT exercises).

New Discoveries

2011 Patent filed "Adaptive Control for Nonlinear MIMO Systems in the Presence of Cross-Coupling" (with C. Cao and E. Xargay)